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Conceptual Design, Feasibility and Payoff Analysis of a Third Stage for EELV

July 30th, 2014

AIAA-2014-3875

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Air Force Research Laboratory

R. Walsh

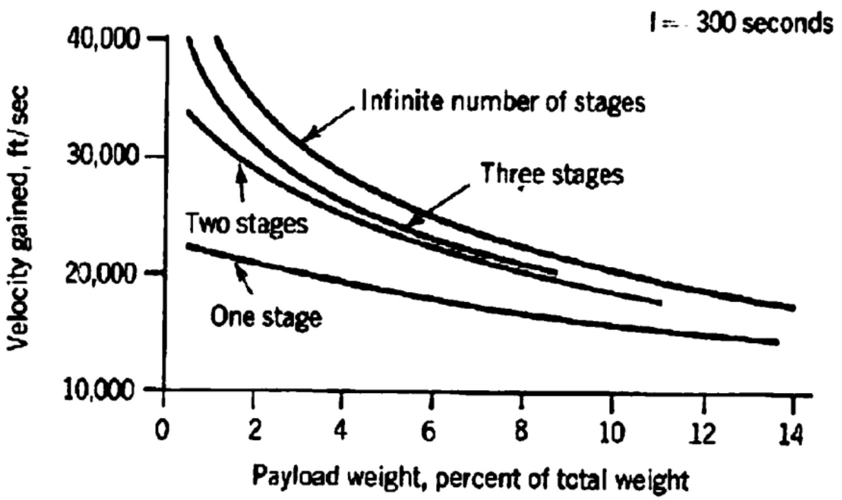
Integrity ★ Service ★ Excellence

Background

- Analysis intended to evaluate the impact a 3rd stage would have on an EELV
  - First order analysis intended to narrow down trade space for future trajectory analysis
  - Too many possible configurations
  - Identify conceptual stage layout
- Analysis is limited to a conceptual level
  - Define 3rd stage requirements from vehicle
    - Select vehicle
    - Define internal volume capacity
    - Define feasible integration scheme
  - Tank shape trade
  - Pressurization configuration trade
  - Propellant trade
  - All-up performance calculation
    - LEO, GTO, High ΔV (interplanetary)
- Analysis used to gain insight of role different performance parameters play in performance

Motivation

- **Advantages:**
  - More stages generally means more payload performance
  - Additional propellant capacity within basic architecture
  - Additional potential side benefits
    - "GTO" kick stage
    - Allows disposal of 2nd stage
    - Smaller on-orbit transfer stage could increase time between station and transfer burn
- **Disadvantages**
  - Non-optimal design assumption
    - Starting from a previously design architecture
  - Performance gains might be minimal compared to increased GLOW configurations



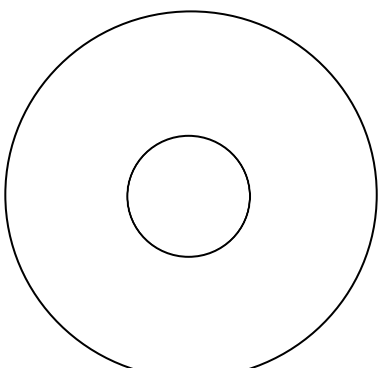
Analysis Scope and Assumptions

- **Baseline vehicle selection**
  - **EELV - specifically Atlas V (500 series configurations)**
- **Identify 3rd stage location**
  - **Will dictate volume and shape restrictions**
  - **Only two feasible areas identified**
    - **Below payload envelope**
    - **Lower section of payload envelope**
  - **Selected areas similar within Delta IV and Atlas V**
- **Identify feasible tank shapes to maximize propellant load-out**
  - **Toroidal**
  - **Oblate spheroid (2:1)**
- **Due to expected small stage size, propellant pressurization scheme is in question**
  - **Pump fed vs pressure fed**
  - **Chamber pressure (I_{sp} vs mass fraction)**
- **Propellant combinations investigated for performance capability**
  - **Hydrazine, N_2O_4/MMH, LOX/RP, H_2O_2/RP, LOX/CH_4, LOX/LH_2 (MR of 6), and LOX/LH_2 (MR of 10)**
- **Propulsion system split into multiple chambers to maximize potential area ratio attainable within axial length**
  - **4 chambers with a combined thrust of 66.72kN (15,000 lbf)**

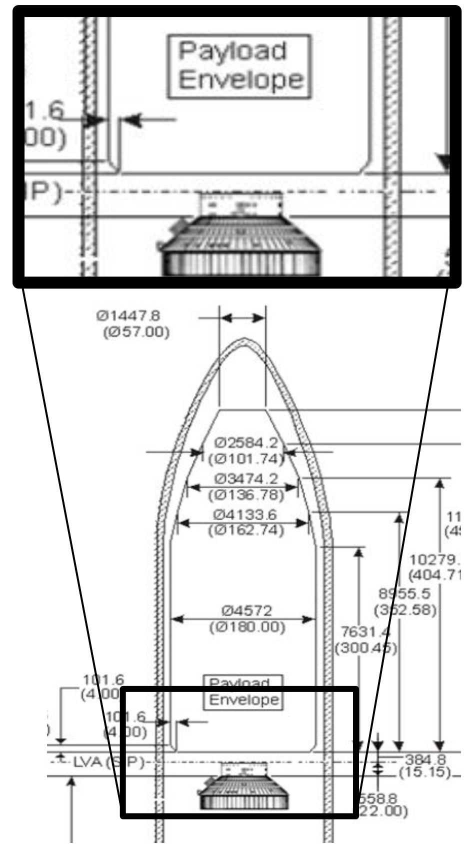
Envelope Requirements

- **Mechanism for integration**
  - **Use of D1666 payload adaptor or ESPA (EELV Secondary Payload Adapter) ring**
  - **Usable volume restricted to external region of adaptor or ESPA ring**
  - **Thick washer or “rectangular donut” shape**
    - **Height: ~35 in**
    - **OD Of Annulus: ~196 in**
    - **ID Of Annulus: ~65 in**
    - **Annulus Delta Radius: ~66 in**

Top View



Side View

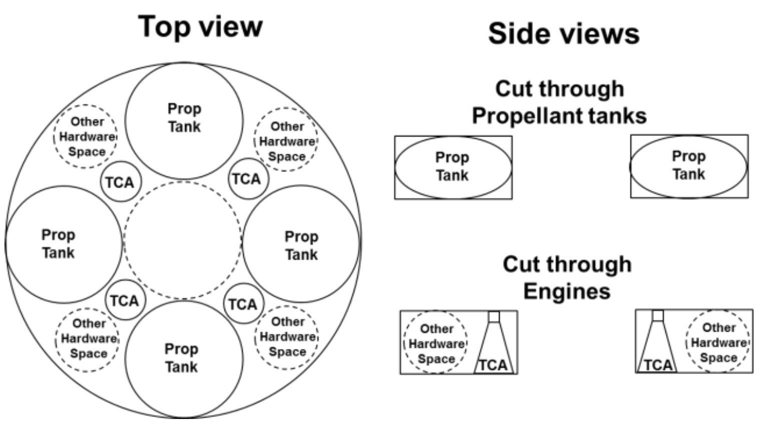


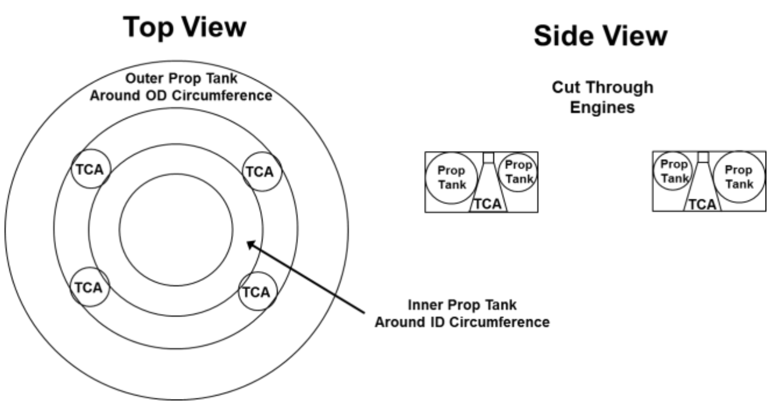
Atlas V 500 series payload fairing

Propellant Tank Configuration

- **Oblate spheroid**
  - 4 spheroid tanks
  - 2:1 ellipse
  - TCAs located near the inner diameter (payload ring)

- **Two toroidal tank subconfigurations:**
  - Monopropellant has only one toroid
    - TCAs located near the inner diameter (payload ring)
    - Propellant tank abutted to outer diamter
  - Bipropellant combinations have two concentric toroid tanks
    - TCAs located in-between tanks

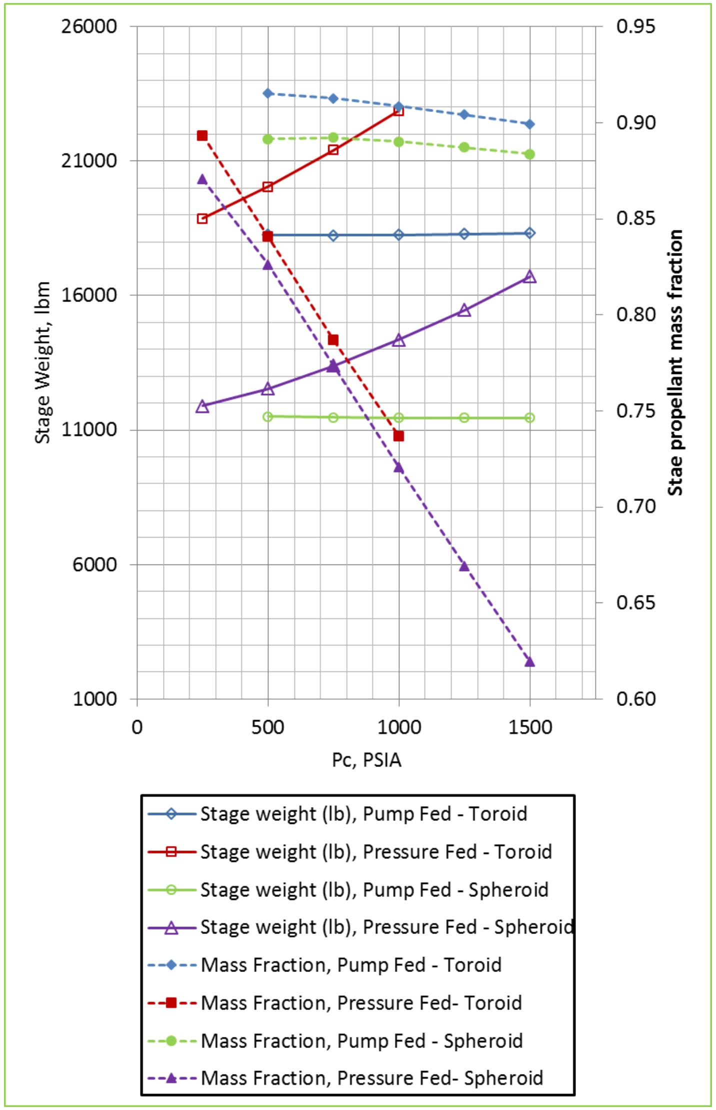




- **Each configuration was analyzed with pressure fed and pump fed pressurization schemes**

Pressure Fed vs Pump Fed

- **Monopropellant hydrazine was used as a baseline for initial pump vs pressure fed comparison**
  - **High bulk density**
  - **Non-cryogenic**
  - **Simplest tank configurations – tends for high mass fraction**
- **Pressure fed uses helium pressurization in high pressure bottles**
- **Pump fed uses a GG system**
  - **Tank pressurized to 172kPa (25psi)**
  - **Helium mass allocated for spin start**
- **I_{sp} determined by area ratio attainable within 35in height**
  - **P_c is main driver**
- **Pump fed was clear winner**
  - **Perhaps if stage volume allowed for a singular spherical vessel pressure fed would be more attractive**



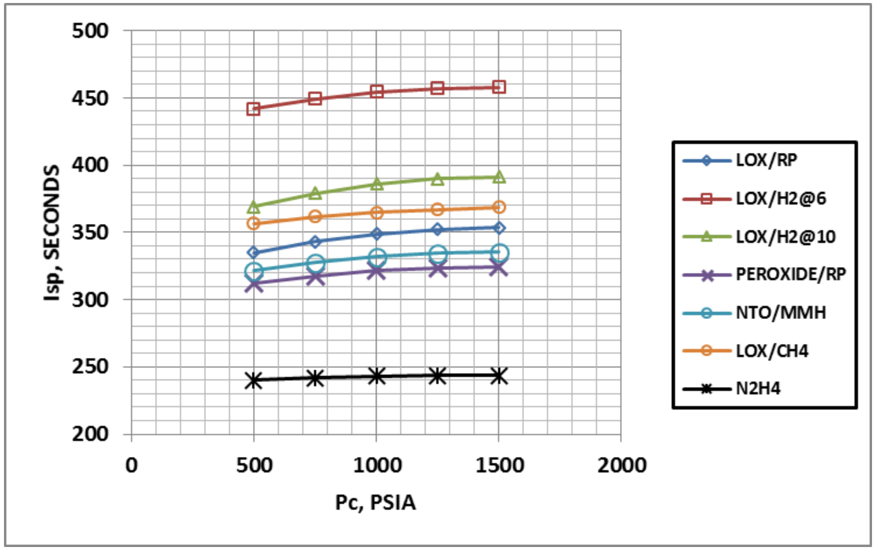
Commentary of Propellant Properties

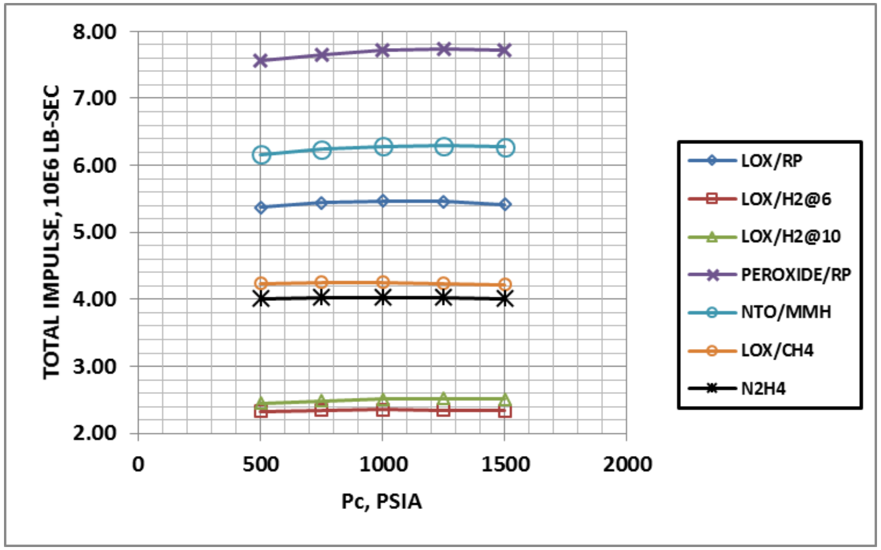
- **Each propellant combination presents different benefits**
  - **NTO/MMH, LOX/RP and Peroxide/RP are dense propellants**
  - **LOX/CH_4 presents an intermediary**
  - **LOX/H_2 offer high I_{sp} at the cost of their bulk densities**
- **The higher the bulk density the more propellant will “fit” within allocated stage envelope**
  - **Higher total impulse**
  - **Higher mass needing to be carried by 1st and 2nd stages**

Propellant type	Mixture ratio	Bulk ρ g/cm3	I_{sp} sec
Hydrazine	-	1.02	*243*
N_2O_4/MMH	1.95	1.2	*332*
LOX/RP	2.8	1.03	*349*
$H_2O_{2(98\%)}/RP$	7.1	1.306	*322*
LOX/CH_4	3.4	0.83	*365*
LOX/LH_2	6	0.362	*454*
LOX/LH_2	10	0.481	*386*

Propellant Combinations: Propulsive Performance

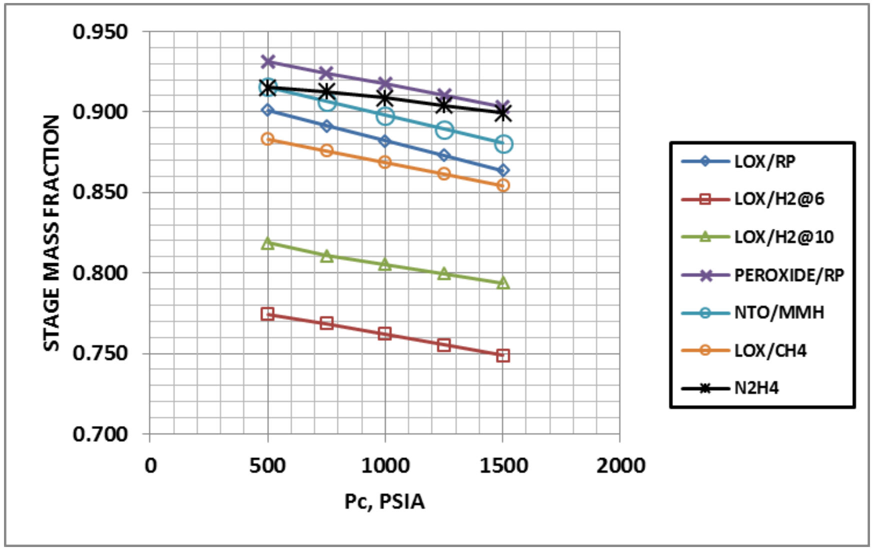
- **Vacuum I_{sp} based on maximum area ratio attainable within length envelope**
  - **Use of four chambers allows area ratios >150**
  - **LOX/LH_2 (MR=6) is highest performing propellant combination**





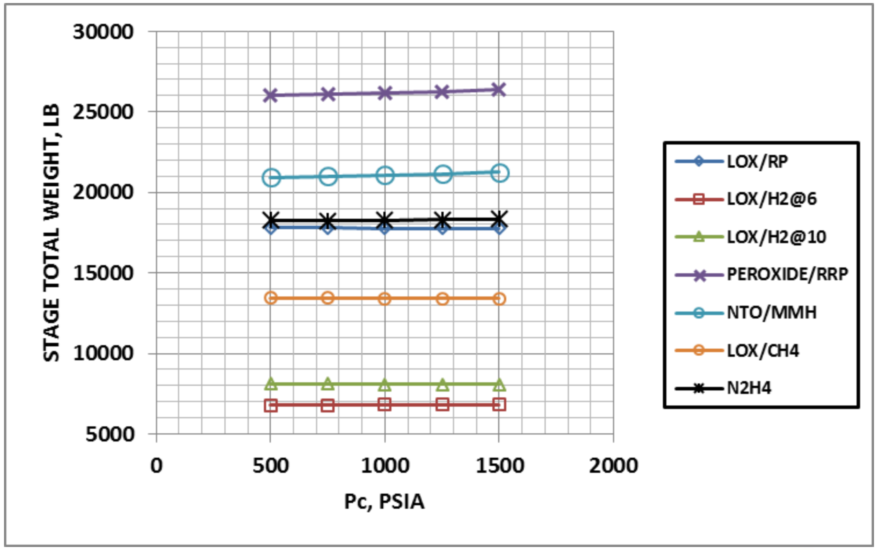
- **Due to LOX/LH2 (MR=6) low bulk density it is not possible to store as much propellant within stage**
  - **Resulting in the lowest total impulse**
- **Peroxide/RP, NTO/MMH and LOX/RP have highest total impulse**
- **What will have greater effect?**
  - **Propellant mass (total impulse) or I_{sp}?**

Propellant Combinations: Mass Efficiency



- Peroxide/RP, NTO/MMH and LOX/RP have highest mass fraction due to their bulk density
  – More propellant able to be carried within envelope
- Overall tankage mass is similar between all configurations due to same stage volume and tank pressure

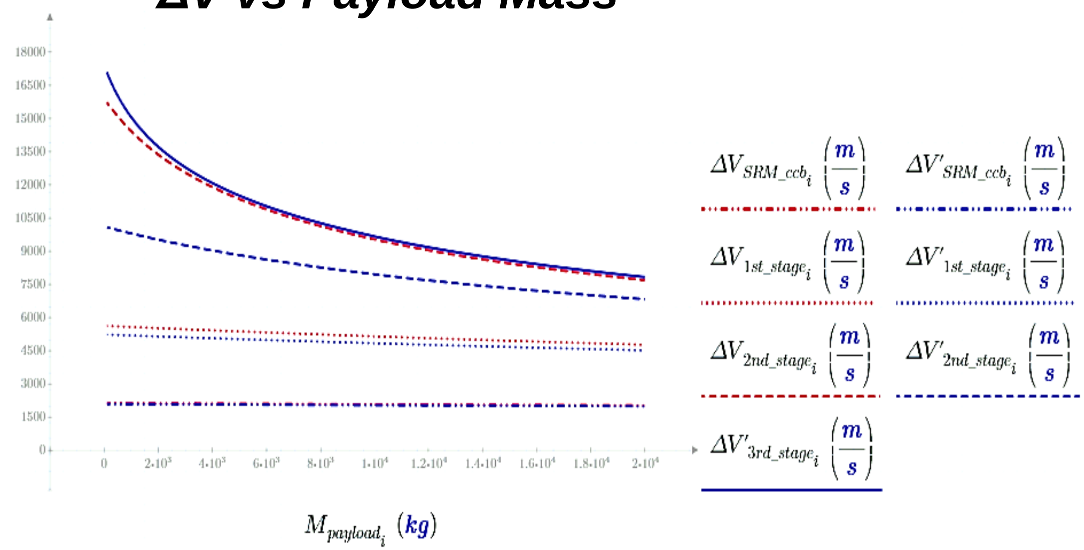
- Mass analysis was based of each individual propellant combination
- Allocating all necessary secondary systems where needed
  – Insulation
  – Heaters (w/batteries)
  – Feed lines
  – Notional structural supports



Vehicle Analysis Procedure

- **Calculations were done with one dimensional rocket equations**
  - No allocation for trajectory losses
  - A calculation with no 3rd stage served as a baseline
  - Computation included all solid motor variations from Atlas 501 to 551
  - Vehicle parameters obtained from Atlas payload user's guide

ΔV vs Payload Mass



Propellant Type's Effect on Vehicle Performance

- An absolute value of payload mass gained is not presented to highlight that at this early conceptual stage
  - Using only percentages restricts the interpretation of results to a comparison between configurations and the baseline EELV configuration
- From the data results a few configurations will be chosen
  - Further detailed trajectory modeling, and thus more detailed payload mass payoff
- A common stage parameter is selected for vehicle performance calculations
  - P_c = 6.9MPa (1000psi)
  - Thrust (stage) = 66.72kN (15000lbf)

	Total Mass		Prop. Mass		Mass fraction	Structural Mass		Isp	Total Impulse	
Propellant. type	kg	lb	kg	lb		kg	lb	s	10^6 lbf*s	10^6 N*s
Hydrazine	*8,283*	*18,260*	*7,526*	*16,591*	*0.909*	*757*	*1,669*	*243*	*4.032*	*17.934*
N2O4/MMH	*9,565*	*21,087*	*8,587*	*18,932*	*0.898*	*978*	*2,155*	*332*	*6.283*	*27.947*
LOX/RP	*8,061*	*17,772*	*7,112*	*15,678*	*0.882*	*950*	*2,094*	*349*	*5.470*	*24.331*
H2O2/RP	*11,878*	*26,187*	*10,895*	*24,019*	*0.917*	*984*	*2,168*	*322*	*7.722*	*34.347*
LOX/CH4	*6,086*	*13,418*	*5,287*	*11,656*	*0.869*	*799*	*1,762*	*365*	*4.255*	*18.926*
LOX/LH2 (MR=6)	*3,084*	*6,798*	*2,350*	*5,181*	*0.762*	*734*	*1,617*	*454*	*2.354*	*10.471*
LOX/LH2 (MR=10)	*3,670*	*8,091*	*2,955*	*6,516*	*0.805*	*715*	*1,575*	*386*	*2.514*	*11.182*
Star 48	*2,165*	*4,772*	*2,035*	*4,486*	*0.940*	*130*	*286*	*286*	*1.300*	*5.782*

3rd Stage Payload Performance Comparison (LEO)

- **For LEO, the greatest improvement by percentage is attained by the use of LOX/LH2 @ MR=6 with a percentage improvement of 8.5%. This is the least dense propellant configuration and the one with the highest Isp.**
  - **Relationship is not strictly due to Isp - methane attains near the same percentage gain**
  - **The top three are LOX/LH2, LOX/CH4, and LOX/RP**
  - **It is interesting to note the Star 48 motor with the highest mass fraction does not greatly affect the delivered payload**
  - **The additional total impulse offered by the additional stage is offset by the losses incurred in the previous stages of having to carry the additional weight**
    - **Not necessarily true for higher ΔV missions**

Atlas V Configurations

Propellant. type	Bulk ρ	Isp	Prop. Mass kg (lb)	501	511	521	531	541	551
Hydrazine	1.02	243	7526 (16591)	*-17.9%*	*-17.2%*	*-15.6%*	*-14.1%*	*-13.3%*	*-13.4%*
N2O4/MMH	1.20	332	8597 (18935)	*4.6%*	*3.6%*	*3.3%*	*3.8%*	*3.4%*	*2.7%*
LOX/RP	1.03	349	7112 (15678)	*6.7%*	*5.1%*	*4.8%*	*5.1%*	*4.9%*	*4.3%*
H2O2/RP	1.31	322	10895 (24019)	*4.4%*	*3.6%*	*3.6%*	*3.9%*	*3.9%*	*3.1%*
LOX/CH4	0.83	365	5287(11656)	*7.8%*	*6.1%*	*5.9%*	*5.6%*	*5.6%*	*4.5%*
LOX/LH2 (MR=6)	0.36	454	2350 (5181)	*8.5%*	*6.7%*	*6.2%*	*6.3%*	*5.3%*	*4.8%*
LOX/LH2 (MR=10)	0.48	386	2955 (6516)	*4.9%*	*3.2%*	*2.8%*	*3.2%*	*2.6%*	*2.0%*
Star 48	-	286	2035 (4486)	*0.7%*	*-0.2%*	*-0.1%*	*0.3%*	*0.0%*	*-0.7%*

3rd Stage Payload Performance Comparison (GTO)

- GTO case follows overall LEO trend
  - Magnitude of percentage improvements increased
  - the off-nominal mixture ratio configuration - LOX/LH2 (MR=10) becomes competitive with LOX/RP, likely demonstrating the reduction of the role total impulse has and an increase on the impact of Isp
- For both the LEO and GTO analysis, the greatest percentage increase occurs in the smaller GLOW configurations (501 vs 551)
  - Mainly due to the smaller baseline payload of the smaller configuration
  - The larger GLOW configuration nonetheless results in a greater absolute payload increase.
    - E.g. a LOX/LH2 (MR=10) LEO configuration has a payload gain is 688kg for 501 and 896kg for 551.

				Atlas V Configurations					
Propellant. type	**Bulk ρ**	**Isp**	**Prop. Mass kg (lb)**	**501**	**511**	**521**	**531**	**541**	**551**
Hydrazine	1.02	243	7526 (16591)	-33.5%	-32.4%	-31.0%	-29.1%	-27.5%	-26.9%
N2O4/MMH	1.20	332	8597 (18935)	8.1%	6.2%	4.8%	4.0%	3.4%	2.8%
LOX/RP	1.03	349	7112 (15678)	14.3%	11.6%	9.6%	8.7%	7.7%	7.1%
H2O2/RP	1.31	322	10895 (24019)	5.7%	4.6%	3.7%	3.3%	2.8%	2.6%
LOX/CH4	0.83	365	5287(11656)	19.6%	17.0%	14.8%	12.7%	11.3%	9.9%
LOX/LH2 (MR=6)	0.36	454	2350 (5181)	24.4%	20.8%	17.7%	16.7%	14.4%	12.8%
LOX/LH2 (MR=10)	0.48	386	2955 (6516)	15.8%	12.5%	10.7%	9.0%	7.7%	7.1%
Star 48	-	286	2035 (4486)	9.1%	6.2%	4.1%	3.0%	2.1%	1.7%

3rd Stage Payload Performance Gain (High ΔV)

- **Special cases where the payload is very small compared to the vehicle weight can pose interesting divergences from LEO and GTO results**
  - Typical of deep space (extremely high ΔV) missions
  - E.g. New Horizon's mission to Pluto launched by Atlas V 551
  - Probe had mass of nearly 500kg and used a Star 48 motor as a final kick stage
- **Analysis based on a small payload to vehicle mass fraction shows the impact of stage mass fraction in these extreme cases**
  - Star 48 motor with high mass fraction performs well against a higher total impulse and Isp stages
  - This hints at a greater role of mass fraction as ΔV increases to extreme cases

Propellant. type	Mass fraction	payload vel (m/s)	payload vel (ft/s)	% improv.
Baseline	-	*15,140*	*49,672*	*0%*
Hydrazine	*0.909*	*14,517*	*47,628*	*-4%*
N2O4/MMH	*0.898*	*15,706*	*51,529*	*4%*
LOX/RP	*0.882*	*16,011*	*52,530*	*6%*
H2O2/RP	*0.917*	*15,647*	*51,335*	*3%*
LOX/CH4	*0.869*	*16,433*	*53,914*	*9%*
LOX/LH2 (MR=6)	*0.762*	*16,893*	*55,423*	*12%*
LOX/LH2 (MR=10)	*0.805*	*16,481*	*54,072*	*9%*
Star 48	*0.940*	*16,854*	*55,295*	*11%*

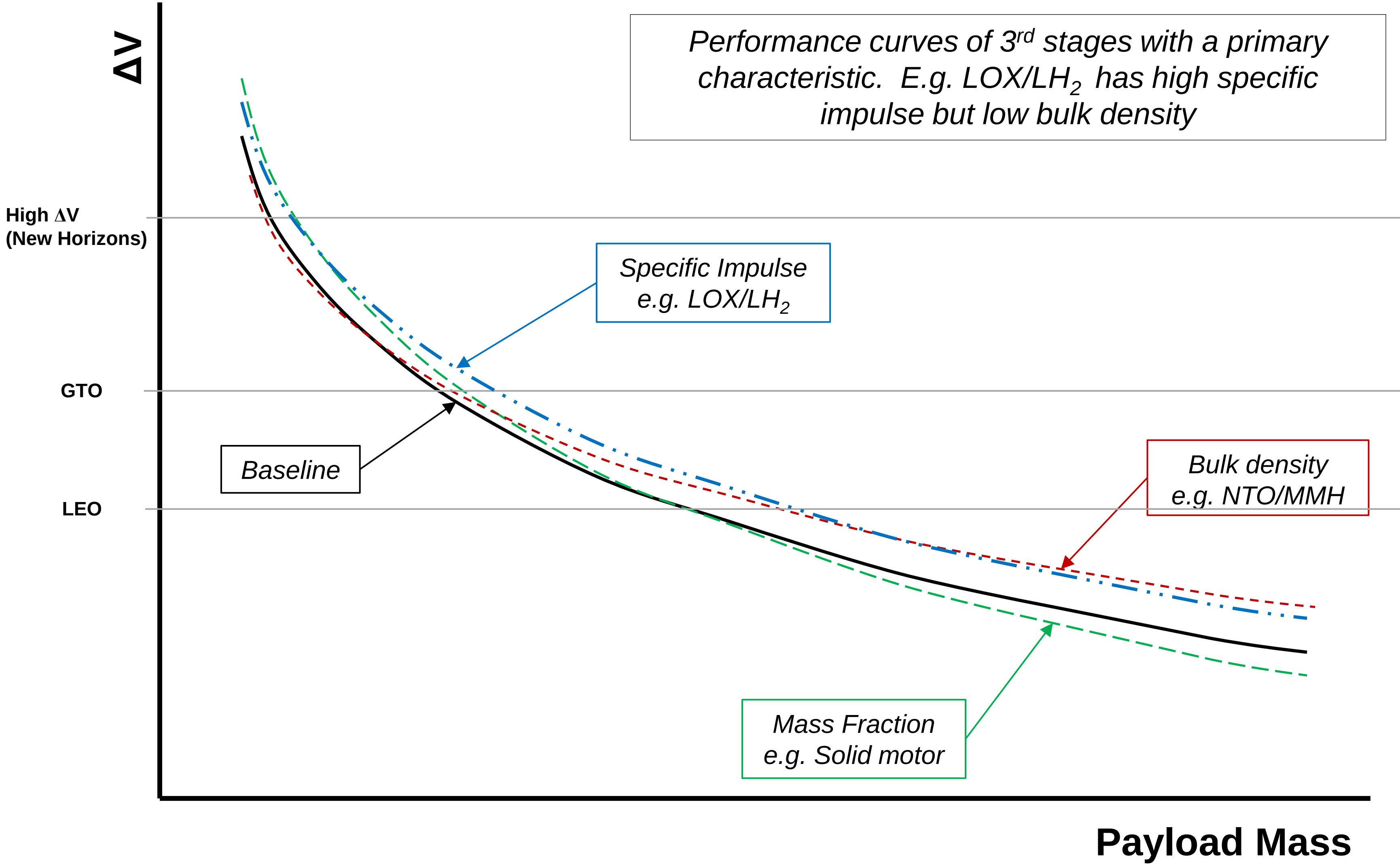
Summary

- Effect of various stage performance parameters' impact upon the payload delivered to a ΔV is complex and requires an analysis that incorporates all the stages
- Third stage implemented within the EELV architecture must have minimal impact to the existing configuration
  - Insertion of an annular stage within the payload adapter envelope allows for low impact
  - Volume and geometry for the stage is significantly constrained
- As such, the balance between propellant bulk density, performance, and mass fraction needs to be quantified
  - Computations show a LOX/LH2 provides the highest performance
    - Even though the bulk density is very low
  - However, a more convenient solution (LCH4) can provide a comparable solution with some operational advantages

Future Work

- A continuation of this calculation will explore the impact of additional propellant volume beyond that restrained by the confined volume
  - Can be attained by the use of a ESPA (EELV Secondary Payload Adapter) ring, and because the geometry configuration is similar, the concept is very adaptable to this integration
- Further non-dimensional analysis will attempt to quantify those parameter relationships
  - $\Delta V = f(I_{sp}, \rho_{bulk}, M_{propellant}, M_{payload}, \ldots ?)$
- Future analysis will also incorporate trajectory performance using POST software to address other factors such as:
  - Initial gravity turn
  - Core engine throttling
  - Gravity losses
  - Multiple burns
  - Parking orbits

Observations of Propellant's Properties Impact Upon ΔV Curve



Back Up – Sample Weight Breakdown LOX/RP pump fed toroid at Pc=1000

LOX/RP BASELINE; TOROIDAL TANKS; LOX IN OD TANK	
STAGE, INPUTS	
ID, FT	5.445
OD, FT	16.4
HEIGHT, FT	2.919
MAX ENGINE EXIT DIA, FT (APPROX)	1.83
OX PROPELLANT TANK NUMBER	1.0
FUEL PROPELLANT TANK NUMBER	1.0
TANK PRESSURIZATION, PSIA	25
OX PRESS COLLAPSE FACTOR	1.25
FUEL PRESS COLLAPSE FACTOR	1.00
OX TANK FOAM THICKNESS, IN	0.75
FUEL TANK FOAM THICKNESS, IN	0
FOAM DENSITY, LB/FT^3	2.4
HE PRESSURANT TANK NUMBER	2
PRESSURE VESSEL SAFETY FACTOR	2
OX TANK TOROID LOCATION	OD
FUEL TANK TOROID LOCATION	ID
OD TORUS CROSS SECTION OD, IN	28.65
OD TORUS CROSS SECTION r, IN (ID)	14.33
STAR 48, INPUTS	
TOTAL IMPULSE, LB-SEC	1.30E+06
TOTAL THRUST, LB	15000
AVG ISP, SEC	286
BIPROP TCA, INPUTS	
MR, O/F	2.8
OX DENSITY, LB/FT^3	71.2
FUEL DENSITY, LB/FT^3	49.9
DELIVERED AVG TCA ISP, SEC	348.80
TCA C*, FT/SEC	5841
ENGINE, INPUTS	
NUMBER	4
NOZZLE AREA RATIO (AR)	150.7
INJECTOR AREA RATIO	4
INJECTOR INLET TO THROAT, IN	6
PC, PSIA	1000
GG MR, O/F	0.310
GG FLOW, % OF TCA TOT PROP	3.819
GG FLOW TURBINE INLET C*, FT/SEC	2428
CALCULATIONS	
STAGE	
TOT HEIGHT, IN	35.0
TOT VOLUME, FT^3	548.6
RING DELTA RADIUS, IN	65.73
PROPELLANT	
BULK DENSITY, LB/FT^3	64.01
TOT TCA FLOW FOR ALL ENGINES, LB/S	43.01
TOT TCA OX FLOW, LB/S	31.69
TOT TCA FUEL FLOW, LB/S	11.32
TOT GG FLOW	1.642
TOT GG OX FLOW, LB/SEC	0.389
TOT GG FUEL FLOW, LB/SEC	1.254
TOT STAGE FLOW (INCL GG)	44.65
TOT OX FLOW, LB/S	32.08
TOT FUEL FLOW, LB/S	12.57
TOT MR, O/F	2.5517
TOT STAGE VOLUMETRIC FLOW (INCL GG)	
TOT OX VOLUMETRIC FLOW, FT^3/S	0.4505
TOT FUEL VOLUMETRIC FLOW, FT^3/S	0.2519
O/F VOLUME RATIO	1.788
F/O VOLUME RATIO	0.559
TOT PROPELLANT (INCL GG), LB: STAR 48 BREAK EVEN	3869.4
TOT PROP VOL, FT^3: STAR 48 BREAK EVEN	60.45

ENGINE	
TCA THRUST, LB	3750
TCA FLOW, LB/SEC	10.75
THROAT AREA, IN^2	2.014
THROAT RADIUS, IN (ID)	0.801
THROAT DIAMETER, IN (ID)	1.602
INJECTOR DIAMETER, IN	3.203
LENGTH: THROAT TO EXIT, IN	27.0
ENGINE TOT LEN, IN	33.0
ENGINE EXIT DIA, IN (OD)	21.2
ENGINE HEAD ROOM, IN	2.0
ENGINE DIA CLEARANCE, IN	0.8
FLUID TANKS	
OX PROPELLANT TANK (OD TORUS)	
OD TORUS MERIDIAN R, IN	84.07
DELTA r FOR SHELL, OTHER, IN	0.50
OD TORUS CROSS SECTION ID r, IN	13.08
OX VOLUME EACH TANK, FT^3	164.24
OX TOT TANK VOL, FT^3	164.24
OX SURFACE AREA EACH TANK, IN^2	43404.7
OX TOT TANK SURFACE AREA, IN^2	43404.7
OX TOT PROP WT, LB	11694
FUEL PROPELLANT TANK (ID TORUS)	
ID TORUS CROSS SECTION OD , IN	27.35
ID TORUS CROSS SECTION OD r, IN	13.67
ID TORUS MERIDIAN R, IN	46.34
DELTA r FOR SHELL, OTHER, IN	0.50
ID TORUS CROSS SECTIO ID r, IN	13.17
FUEL VOLUME EACH TANK, FT^3	91.86
FUEL TOT TANK VOL, FT^3	91.86
FUEL SURFACE AREA EACH TANK, IN^2	24100
FUEL TOT TANK SURFACE AREA, IN^2	24100
FUEL TOT PROP WT, LB	4584
TANK SIZE CONVERGENCE	
TANKED PROPELLANT MR, O/F	2.5513
STAGE FLOW MR, O/F	2.5517
DIFFERENCE	-0.0004
TANK O/F VOLUME RATIO	1.7881
STAGE O/F FLOW VOLUME RATIO	1.7883
HELIUM TANKS	
GG SPIN START FACTOR (0=NONE; 1=USE HE)	1
GG SPIN HE FLOWRATE, LB/SEC WHEN USED, LB/S	1.118
GG SPIN TOT HE WHEN USED, LB	0.559
GG SPIN TOT HE WT, LB	0.56
OX TANK HE	
HE PRESS VOLUME, FT^3	1.74
HE PRESS WT, LB	6.04
FUEL TANK HE	
HE PRESS VOLUME, FT^3	0.78
HE PRESS WT, LB	2.70
TOT HE VOL, FT^3	2.68
TOT HE WT, LB	9.30
HE SPHERE DIA (EACH), IN	16.37
HE SPHERE TOTAL SURFACE AREA, IN^2	1684.30
GG DESCRIPTION	
FLOW, LB/SEC	1.642
STAGE PERFORMANCE	
TOT USABLE PROPELLANT, LB	15679
TOT DEL IMPULSE, LB-SEC	5.469E+06
TOT BURN TIME, SEC	364.6

WEIGHT ESTIMATES	
PROPELLANT TANKS	
OX TANKS	
THICKNESS, IN	0.100
WEIGHT FOR ALL TANKS, LB	434.0
WEIGHT FOR FOAM, LB	45.2
TOT OX TANKS WT, LB	479.3
FUEL TANKS	
THICKNESS, IN	0.100
WEIGHT FOR ALL TANKS, LB	241.0
WEIGHT FOR FOAM, LB	0.0
TOT FUEL TANKS WT, LB	241.0
HE TANK(S)	
THICKNESS, IN	0.102
WEIGHT, LB	49.8
ENGINE(S)	
INJ WALL THICKNESS, IN	0.048
INJ SURFACE AREA, IN^2	92.6
EACH INJ SHELL, LB	1.3
INJECTOR VOLUME, IN^3	8.1
INJECTOR WT, LB	1.2
TOT INJ WT, LB	2.4
NOZZLE AREA, IN^2	950.1
NOZZLE AVG ABLATIVE THICKNESS, IN	0.73
NOZZLE ABLATIVE VOLUME, IN^3	693.1
NOZZLE ABLATIVE WT, LB	36.0
NOZZLE SHELL THICKNESS, IN	0.050
NOZZLE SHELL VOLUME, IN^3	47.5
NOZZLE SHELL WT, LB	13.6
TOT EACH TCA, LB	52.0
TOT VALVES, LB	16.8
TOT ALL TCA, LB	225.0
GG & FLUID SUPPLY	
INJ PACK, LB	10.3
INLET VALVE, LB	2.6
TPA, LB	46.5
TOT GG/TPA, LB	59.3
OX LINES	
PUMP OUTLET PIPE DIA, IN	0.83
PUMP OUTLET PIPE THICKNESS, IN	0.020
PUMP OUTLET PIPE TOTAL LENGTH, IN	411.8
PUMP OUTLET PIPE TOTAL VOLUME, IN^3	21.53
PUMP OUTLET TO PUMP TOTAL WT, LB	6.2
TANK OUTLET PIPE DIA, IN	0.83
TANK OUTLET PIPE THICKNESS, IN	0.0200
TANK OUTLET PIPE TOTAL LENGTH, IN	411.8
TANK OUTLET PIPE TOTAL VOLUME, IN^3	21.53
TANK OUTLET TO PUMP TOTAL WT, LB	6.2
FUEL LINES	
PUMP OUTLET PIPE DIA, IN	0.62
PUMP OUTLET PIPE THICKNESS, IN	0.020
PUMP OUTLET PIPE TOTAL LENGTH, IN	411.8
PUMP OUTLET PIPE TOTAL VOLUME, IN^3	16.10
PUMP OUTLET TO PUMP TOTAL WT, LB	4.7
TANK OUTLET PIPE DIA, IN	0.62
TANK OUTLET PIPE THICKNESS, IN	0.020
TANK OUTLET PIPE TOTAL LENGTH, IN	411.8
TANK OUTLET PIPE TOTAL VOLUME, IN^3	16.1
TANK OUTLET TO PUMP TOTAL WT, LB	4.7
TOTAL PROPELLANT PIPING WT, LB	21.8
STAGE OUTER SHELL	
AREA, IN^2	28008
THICKNESS, IN	0.04
VOLUME, IN^3	1120
WEIGHT, LB	112.0
COMPONENT DRY WEIGHT TOTAL	1188.3
STRUCTURE, LB	118.8
CONTINGENCY, LB	178.2
TOTAL DRY WEIGHT, LB	1485.3
TOTAL FLUID WEIGHT, LB	16287.0
TOTAL STAGE WEIGHT, LB	17772.3
TOTAL USABLE PROPELLANT, LB	15678.9
STAGE MASS FRACTION	0.8822